

## Replenishment Differences in EHL Contact Lubricated by New and In-bearings-aged Grease

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### ABSTRACT

*In-contact replenishment differences between new and aged grease are studied using ball-on-disc optical fluorescence. Three different greases were aged in rolling bearings for 30 – 50 % of their predicted life. A considerable effort is focused on fluorescence calibration, so that differences in lubricant volume can be quantified. No changes in replenishment between new and aged samples were found in one grease. The other two greases were contaminated by metal particles and iron oxide powder. Grease fluorescence was quenched by contaminants and linear relation between intensity values and film thickness did not apply for samples with heaviest contamination. Nevertheless, strong link between the degree of contamination and lubricant replenishment was found.*

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## 1. INTRODUCTION

Grease is currently first choice for general lubrication in rolling bearings, unless operating conditions demand otherwise. Due to its consistency the grease is kept in bearings and starts to function partly as a seal, which allows for low maintenance operation. Bearings lubricated with grease undergo two phases, according to Lugt [1]. Initially, churning phase is carried out. During this phase, film thickness is higher than with oil lubrication, grease is heavily worked, slowly being pushed away from the contact. The operating temperature is relatively high and it can last for several hours. It is highly recommended to start bearing operation with running-in procedure, slowly increasing operating load to prevent

overheating. The churning phase is over when no more grease can be pushed away, and lubricating film consists of degraded thickener and hydrodynamic layer of oil [2]. Reservoirs of grease are formed, either on bearing shoulders [3] or under the cage [4]. Oil is then released from thickener in a process called bleeding, due to combination of gradual mechanical degradation of thickener structure and bearing temperature. Secondly, bleeding phase of grease lubrication takes place. Oil from the grease replenishes the track as observed by Kostal et al. [5], [6]. Wikstrom and Jacobson [7] states that the amount of lubricant in the contact is a balance between the amount of oil bled from grease reservoirs into the contact and the amount of oil lost from the contact by e.g. evaporation. Lubricant availability is even

lower for succeeding contacts in multiple contact system, such as rolling bearing as was observed by Kostal et al. [8], [9]. However, during most of the bleeding phase, friction is more favorable than with oil lubrication, because starvation occurs much more regularly, rather than fully flooded regime, according to Lugt [10] and as observed by Svoboda et al. [11]. Starvation is especially frequent under transient conditions as shown by Svoboda et al. [12]. Specific behavior can be also influenced by grease structure as shown by Sakai et al. [13]. Film thickness during bleeding phase is not constant. Mas and Magnin [14] state that film is broken many times during bearing life. That is accompanied by increased temperature, which causes higher oil bleed rate from reservoirs and film recovery. Lugt et al. [15] later corroborates these observations and calls them chaotic behavior of grease.

However, the amount of bleed oil available from the lubricant reservoirs is not unlimited. Grease is slowly being broken down during service. This degradation can be of either chemical or mechanical nature. Booser and Khonsari [16] describes, that chemical degradation occurs as a product of oxidation reactions occurring during increased temperatures. Oil evaporation and high bleed rates are also associated with the high temperatures. Mechanical degradation can be caused by either loss of the base oil from grease or destruction of the thickener structure. Rezasoltani and Khonsari [17] states that chemical degradation has no significant effect when operating at regular temperatures and destruction of thickener structure due to mechanical working of the grease is the most significant grease degradation happening.

Rezasoltani and Khonsari [17] describes mechanical degradation as irreversible action, which eventually results in grease losing its ability to replenish contact. Part of the energy generated by bearing is dissipated inside grease, causing breakage of thickener structure and subsequently softening the grease. Two categories of tests are currently used to determine grease degradation and those are either shear or mechanical stability tests. During the shear stability test, such as ASTM D217 “grease worker”, only shear is applied. Mechanical stability tests are particularly useful for situations where grease was subjected to vibrations and continuously worked. Roll stability

test (ASTM D 1831) is an example. Quality of these tests is largely determined by their ability to predict real world degradation of grease. Zhou et al. [18] notes that Roll stability test proved successful for prediction of conditions in automobile or railway wheel bearings. The same does not apply for the grease worker test as shown by Lundberg and Berg [19].

Although grease degradation has been attracting increasing attention, the effect of grease age on its actual replenishment capability has not been studied so far, at least for age comparable to total grease life. Artificial aging of grease in laboratory is used much more frequently than grease aged under real conditions, as it cheaper and less time demanding. However, laboratory test results can fail to correctly predict situation in real world.

Therefore, the aim of this study is to compare replenishment behavior of new grease and grease aged in rolling bearings to discover if replenishment performance is changing during grease aging. Main parameter for evaluation is the replenishment time after stop of the rolling motion.

Most suitable observation method to achieve the goal is fluorescence microscopy. Fluorescence was first used in tribology by Smart and Ford [20] and further developed by Sugimura [21], who observed films as thin as 30 nm. He also noted that the effect of internal light interference and background light for steel-glass contacts makes reliable and precise thickness calibrations difficult. Azushima [22] demonstrated linear dependency between observed light values and film thickness for thickness between 5 – 13  $\mu\text{m}$ .

## 2. MATERIALS AND METHODS

Following materials and procedures were employed for the purpose of this study.

### 2.1. Lubricant samples

Table 1 lists properties of three chosen commercially available all-purpose greases. All three greases are mineral oil based with lithium thickener. It was selected because according to NLGI report [23], lithium based greases make up to 70 % of global grease sales. Thickener is

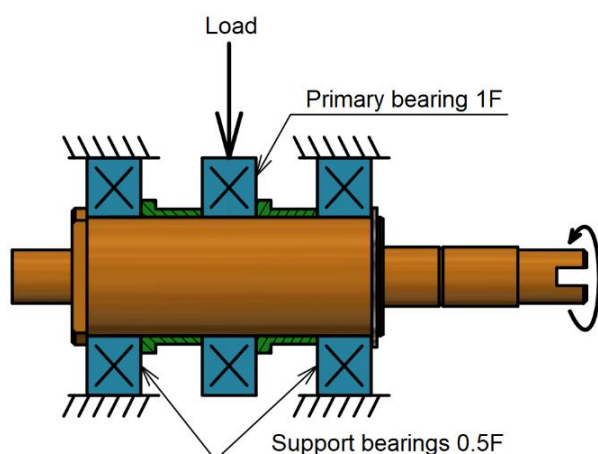
described to have short-fiber structure for all three greases. The properties of chosen greases are similar, the greatest difference between them being different base oil viscosity. All greases contain antioxidants and corrosion inhibitors and M2 and M3 contain also extreme-pressure additives (EP).

**Table 1** Properties of used grease.

Grease reference	M1	M2	M3
Base oil kinematic viscosity at 40 °C [mm <sup>2</sup> s <sup>-1</sup> ]	50	130	200
Recommended operating temperature [°C]	-30-120	-30-120	-25-120
Penetration at 25 °C (ISO 2137) [10 <sup>-1</sup> mm]	230-270	250-290	260-300
NLGI Grade [-]	2-3	2	2
Dropping point (ISO 2176) [°C]	185	180	180

## 2.2. Grease aging

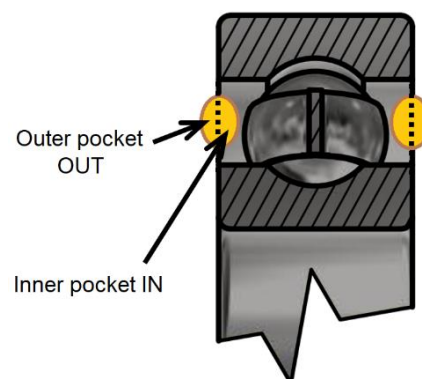
Aging of the greases was carried out in bearing rigs (Fig. 1) using 6208 deep-groove ball bearings. Rigs are equipped with contact probes monitoring vibrations and temperature at the outer ring of the primary bearing. Operating conditions were set so that the recommended re-lubrication intervals were as short as possible, while keeping the occasional temperature peaks less than 120 °C, which is the maximum recommended operating temperature for both the testing rigs and greases. The operating conditions meeting these requirements were found to be a load of  $F=4$  kN and  $n=6100$  RPM.



**Fig. 1.** Bearing station used for grease aging.

The average temperature under these conditions was 50 – 55 °C for various greases. The lubricating interval for these conditions is

2000 – 3000 hours, according to various prediction models found online ([24], [25], [26]). The total runtime of the bearing rigs was planned to be 1000 hours. Initial running-in of the bearings was done by slowly increasing the load under constant speed.



**Fig. 2.** Distribution of aged grease in bearing.

Only M1 was successfully run for 1 000 hours. M2 and M3 were stopped at 850 and 900 hours respectively, due to excessive vibrations. Sample M2 was found to be contaminated by fine iron oxide (IO) powder caused probably by one of the spacing rings. M3 grease was later examined and contamination by metal particles (MP) was found. However, bearing did not show signs of pitting. When the rigs were disassembled most of the grease was found in pockets near cage, as is illustrated in Fig. 2. Very limited quantity of grease and oil was found in cage cavities and raceways, but the amount was insufficient for experiments. Pocket contents were divided into two parts – inner and outer layer and will be referenced as IN and OUT respectively. Whether the grease was worked in primary (1F) or support bearing (0.5F) was also distinguished between. Total of 12 samples were acquired – four per each aged grease.

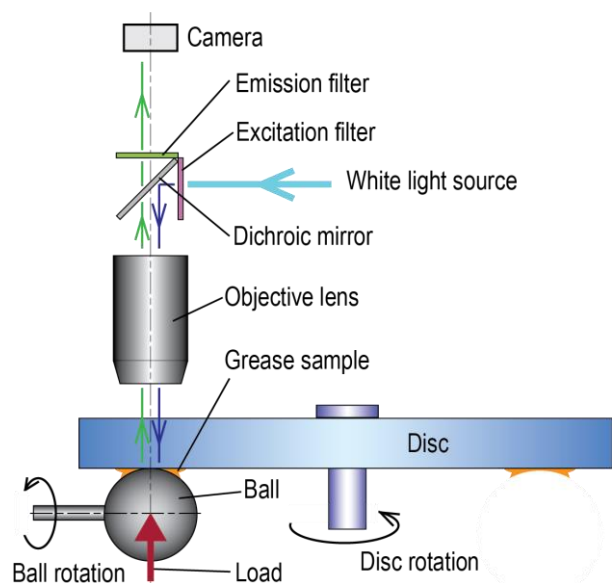
## 2.3. Experimental equipment and methods

Tests were performed on a ball-on-disc tribometer presented schematically in Fig. 3. Both rolling elements are independently driven by servomotors. Contact load is created by lever mechanism connected to the disc. The ball is made from AISI 52100 (100Cr6) bearing steel with a diameter of 25.4 mm. The disc is manufactured from BK7 glass. It is 12.7 mm thick and has a diameter of 150 mm. Ball and disc properties are presented in Table 2. Imaging part of testing rig consists of mercury

lamp, fluorescent microscope, sCMOS digital camera and PC for camera control and data acquisition.

**Table 2.** Properties of contact bodies.

	Ball	Disc
Elastic modulus [GPa]	210	82
Poisson coefficient [-]	0.3	0.21
Contact curvature R [mm]	12.7	$\infty$

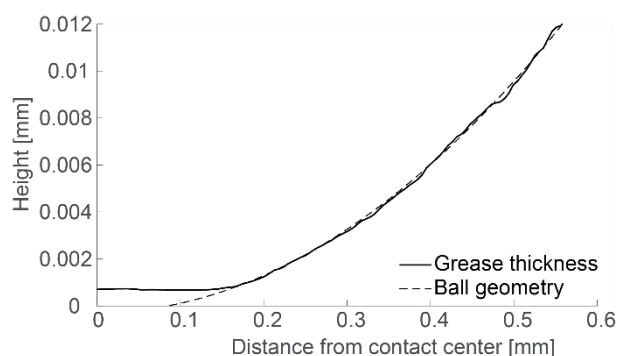


**Fig. 3.** Schematic view of ball-on-disc apparatus.

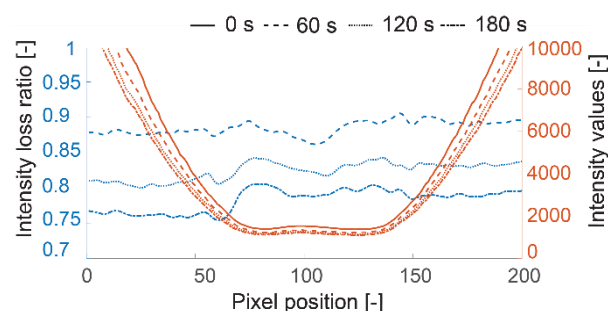
#### 2.4. Fluorescence method, calibration

Fluorescence can be used in situations where oil film is split and air is present in between, allowing for observation of grease in wider area around the meniscus and contact. Mineral oils are naturally fluorescent under UV light, so no dyes need to be mixed in.

For comparing different samples, quantitative observation must be used. Therefore, calibration for specific film thickness must be included in the experiments. The observations happen exclusively after stopping the motion. Therefore, fully flooded contact with significant meniscus can be observed each time. Intensity values of bleed oil meniscus around the contact were multiplied by single coefficient to fit the film thickness expected from contact geometry. Resulting fit can be seen in Fig. 4. Agreement between lines is acceptable for the purpose of this study. It also reaffirms linear dependence between observed intensity values and grease thickness, at least for films 1 – 12  $\mu\text{m}$  thick.



**Fig. 4.** Calibration of observed light values to calculated geometry.



**Fig. 5.** Photo bleaching observed over 180 seconds for M1 grease; ball geometry with pronounced.

The small area of grease is being illuminated for the duration of each individual measurement (180 seconds) because only static contact is observed. Photo bleaching (PB) effect, that is causing decrease of observed light values over time for constant film thickness, can be significant. Static fully flooded contact was observed for 180 seconds for all three greases. Several images were recorded at different times since the light shutter was opened. Intensity loss ratio was calculated for each pixel in image from intensity in the first and current image. Intensity loss ratio for M1, which was the most susceptible to PB, is shown in Fig. 5. Approx. 20 % less intensity values were observed after 180 seconds. For samples M3 resp. M2 the observed light values loss was only 1 % (5 % resp.). Three conclusions concerning PB are drawn:

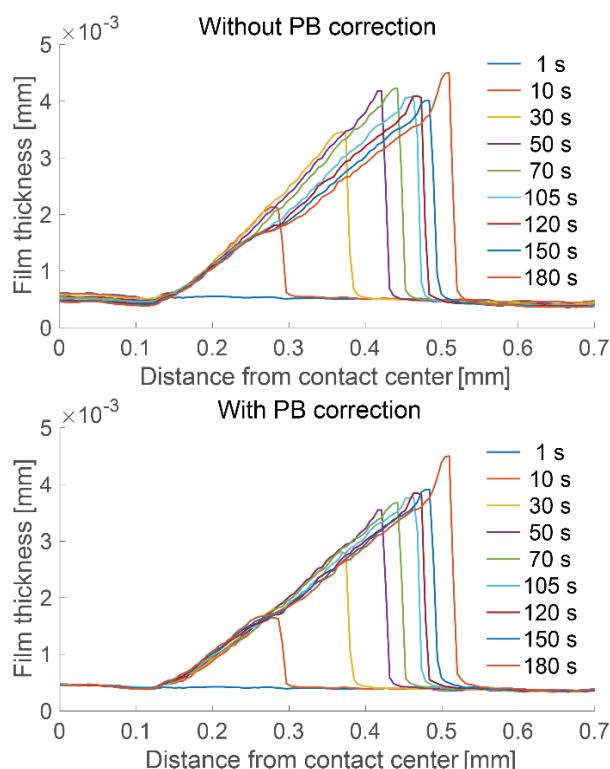
1. PB is constant for varying lubricant thickness.
2. Light loss ratio in Hertz area is roughly equal to the rest of image.
3. PB is not constant over time.

Photo bleaching (PB) coefficient  $C_i$  was proposed to counter PB effect:

$$C_i = \frac{x_n}{x_i} \quad (1)$$



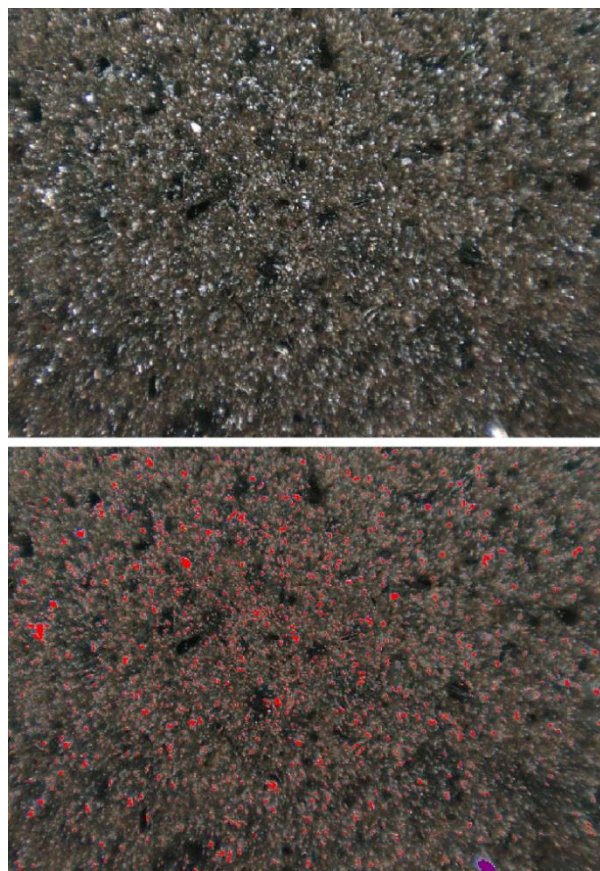
where is  $x_n$  is the sum of values in Hertz area in the last image and  $x_i$  is the sum of values in Hertz area in the “i” image. Each image was then corrected by its individual PB coefficient  $C_n$ . The last image is used for thickness calibration. Therefore, the PB coefficient is calculated using last image as well. However, it is possible that contact film thickness in Hertz area could change after the motion is stopped, because film thickness has no longer hydrodynamic component. That would mean that proposed procedure will not work as  $C_n$  would not be controlled by only PB effect. Identical images were therefore compared before and after the PB coefficient was applied to verify performance of PB correction. The difference can be seen in Fig. 6 where slices of one half of a contact with growing meniscus are displayed. Individual slices are shot 20 – 30 seconds apart. Meniscus shape filling the space between ball and disc changes greatly when the PB correction is not applied.



**Fig. 6.** Meniscus slices parallel to the ball path during 0 - 180 seconds after stopping, without PB correction (upper) and with (bottom).

Another easy correction is for the background light always present in the image. Contact with no grease was recorded and its average intensity values were subtracted from recorded images of lubricated contact to remove

background light. It originates from elsewhere outside of the microscope.



**Fig. 7.** Contamination analysis, 15 % of evaluated area for M3 1F IN (up – microscope image with reflective particles, bottom – contamination evaluation – red areas).

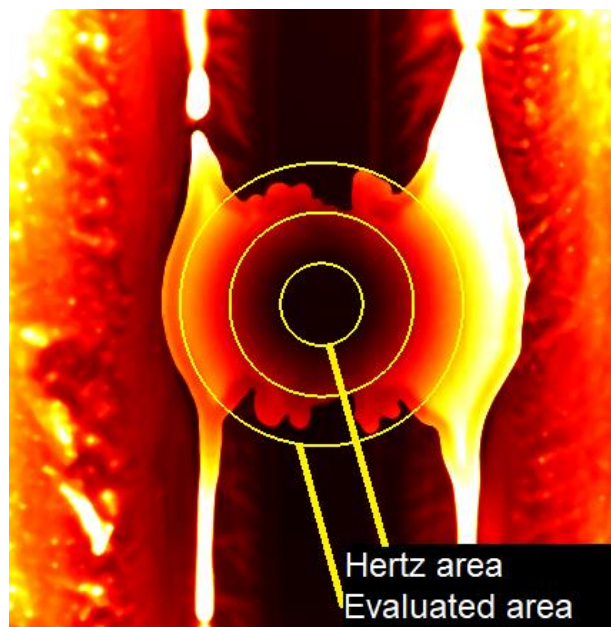
## 2.5. Analysis of contaminated samples

Optical microscope Keyence VHX-650E with white light was used to capture images of 50  $\mu\text{m}$  thick film of aged grease samples to quantify contamination. Thickness was controlled by circular precision metal shim pressed between two optically flat glasses. Observed images were then processed with Contamination analysis software, included with the microscope, to find metal particles highly visible under the illumination. Used method is compliant with ISO 16232. Analyzed image segment for M3 1F IN sample, which was contaminated the most, can be seen in Fig. 7. M2 grease was found to have significant contamination by IO powder. It was undetectable by the method above, because rather than contaminant particles, contamination manifested by color change of the sample. Therefore, rather crude method was

used. Images from the optical microscope were analyzed and all pixels with color close to contamination color were counted.

## 2.6. Experiment procedure

This study describes observation of the behavior of grease around the contact after the ball-on-disc motion was stopped – this approach was selected to better describe ability of grease to replenish depleted areas. Stationary contact with significant meniscus 180 seconds after the motion was stopped can be seen in Fig. 8. Hertz area is highlighted, together with area of interest in which the grease volume was quantified. Diameter of the evaluated area is 1 mm, which is roughly comparable to horizontal spacing of vertical grease shoulders visible at each quadrant around the contact. Although the area of interest is completely filled with grease in some cases, this dimension was chosen after several tries as a compromise. If the area is greater, measurement scatter increases due to higher variation of grease present in the area from the beginning. Smaller areas were filled completely for majority of tested samples and very small differences between samples were observed.

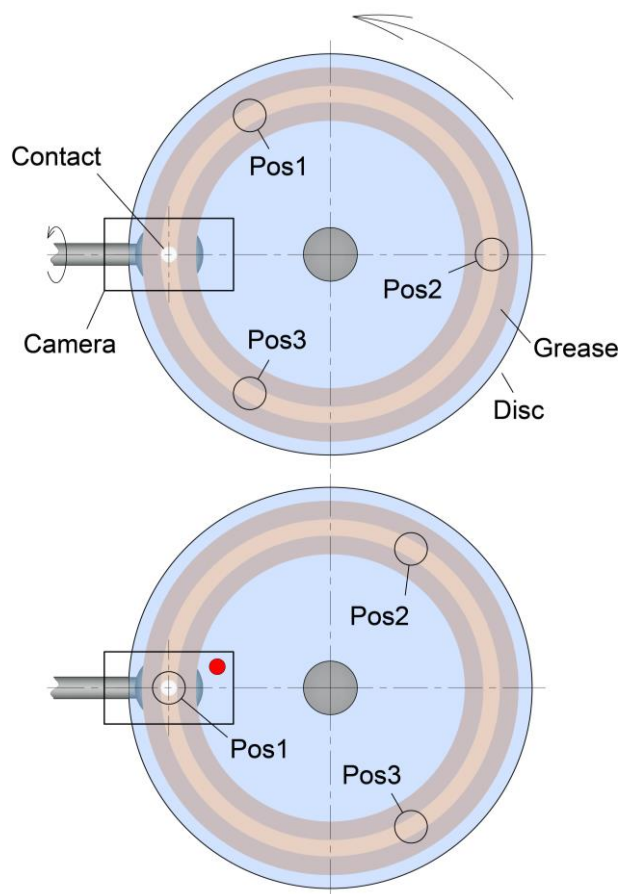


**Fig. 8.** Area of interest for grease volume evaluation (M3, 1000 disc revolutions, 180 seconds after stop).

Each grease sample was measured in the following way:

1. 50  $\mu\text{m}$  thick layer of grease was spread onto the disc at the start of the experiment.

2. Contact was loaded by 35 N.
3. Ball and disc were rotated with pure rolling motion (Fig. 9, up). Entrainment speed was set to 0.1 m/s for the first 10 revolutions of the disc, so that the grease was not worked too unpredictably in higher speeds during the initial stage of experiment. After that, the speed was increased to 0.35 m/s.



**Fig. 9.** Experiment procedure (up – rotation, bottom – recording).

4. Motion was stopped and contact was recorded at POS1 when the required amount of disc revolutions was reached (Fig. 9). The recording contains deceleration and the following 180 seconds of static contact, during which lubricant flows into contact. After the recording was complete, the motion was turned on again and stopped shortly after to repeat the recording for the same number of disc revolutions two more times (POS2 and POS3 in (Fig. 9). Random scatter was found between the three measurements, but no systematic increase or decrease of volume was found.

5. Grease was worked until the next required amount of revolutions and step 4 was repeated. Recordings were done at 10, 100, 200 and 1000 total disc revolutions.
6. Grease was wiped and spread onto disc again when the recordings at 1000 revolutions were completed. The whole process was repeated for the second time. Therefore, every sample was recorded 6 (3+3) times in total for each number of revolutions.
7. Grease can behave unpredictably, so maximum and minimum values from each set were removed, and the results were calculated from 4 middle values.

### 3. RESULTS AND DISCUSSION

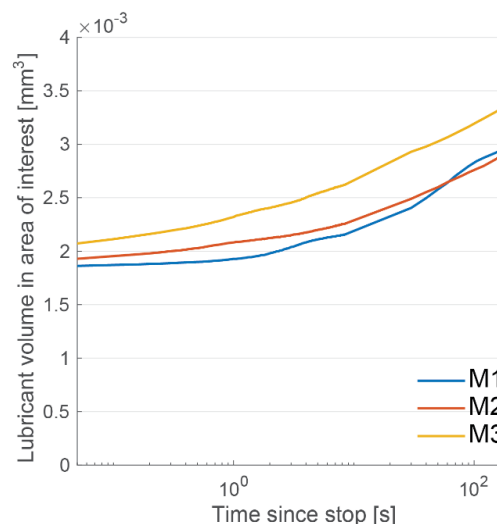
The effect of several different parameters on grease behavior was studied. In the following chapter, grease samples acquired from bearings will be distinguished based on location they were extracted from (see Table 3). Results for grease after 1000 revolutions on the testing rig will be shown, unless specified otherwise. Volume of lubricant in the area of interest 180 seconds after the contact is stopped will be referenced as total (lubricant) volume.

**Table 3.** Differentiation of samples as per Fig. 1 and Fig. 2.

Label	Sample source
1F IN	Inner layer from primary bearing
1F OUT	Outer layer from primary bearing
0.5F IN	Inner layer from support bearing
0.5F OUT	Outer layer from support bearing

#### 3.1. Influence of base oil viscosity

Development of lubricant volume during 180 seconds after the motion is stopped for new greases is displayed in Fig. 10. Observed lubricant flowing into the contact after the motion is stopped acts as a fluid, confirming that the majority of lubricant replenishing film thickness is bled oil. A relation between base oil viscosity and initial lubricant volume can be seen. Lubricant present in area of interest immediately after stopping roughly translates to the amount available for moving contact, meaning that base oil viscosity can influence the amount of lubricant present in meniscus during motion as expected.



**Fig. 10.** Volume of lubricant observed for new greases.

However, volume of lubricant flowing into contact during the observation does not correlate with viscosity. The same effect of base oil viscosity was not found for most aged greases. The only exception was 0.5F IN samples that have the lowest average levels of contamination.

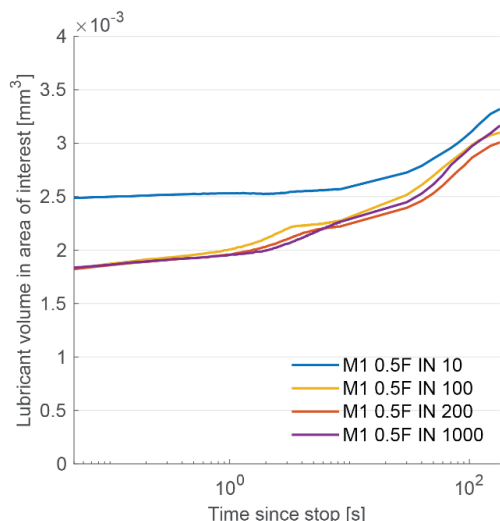
#### 3.2. Uncontaminated M1 grease samples

Typical behavior of uncontaminated samples with increasing number of disc revolutions done can be seen in Fig. 11. Highest initial volume is observed at 10 revolutions for all M1 samples, both new and aged. On the other hand, the amount of new lubricant flown into the area of interest during the 180 seconds of observation is lowest at that point. This indicates that running in procedure is in process and examination of the recorded images confirms this – for most samples, the typical butterfly shape of meniscus is formed between 10 and 100 revolutions Fig. 12. Also, the amount of lubricant flowing into contact after the motion is stopped generally increases during this period. Between 100 – 1000 revolutions, both initial volume and lubricant flow generally stabilize. Although slight deviations in lubricant volume are observed for different number of revolutions done, no general trend can be found across all samples.

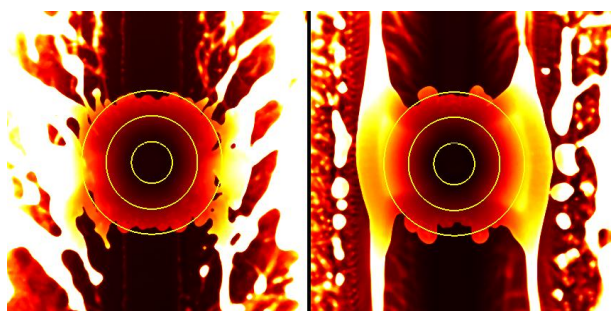
Aged M1 samples can be divided in two ways to highlight potential effects acting on grease during service: distinction by operation load (1F, 0.5F) and distinction by point of extraction (IN, OUT). Inner layers have slightly higher total



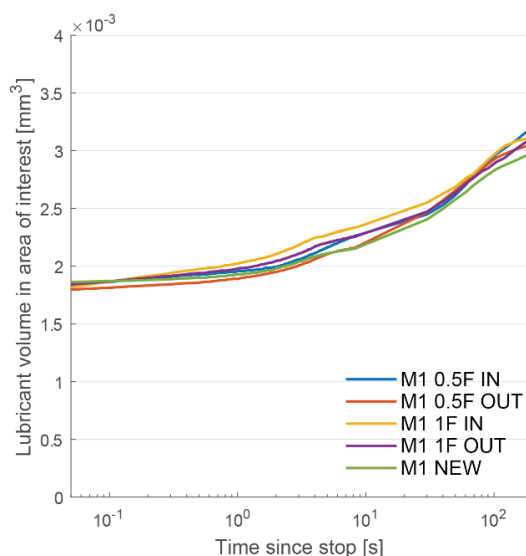
volume in Fig. 13. Since only inner layer connects the outer layer to the bearing, the inner layers could have acted as a dampener, reducing the vibrations transferred to the outer layer, thus limiting the degree of mechanical degradation of outer layer.



**Fig. 111** Flow of lubricant into contact with increasing revolutions for M1 0.5F IN sample.



**Fig. 12.** Change of contact surroundings after running in (M1 1F OUT, 10 rev. left, 100 rev. right).

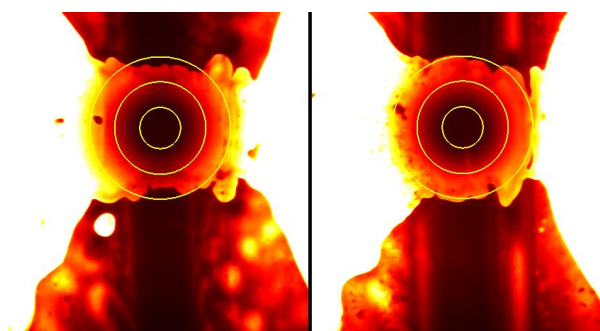


**Fig. 13.** Development of lubricant volume for M1 samples at 1000 done revolutions.

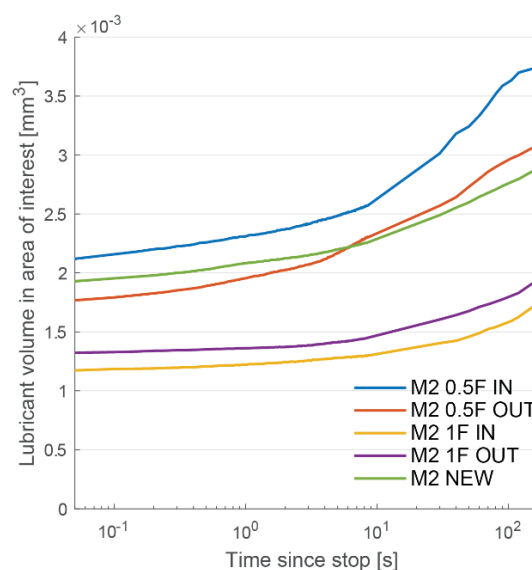
The difference is very small, so it could also be only noise. No significant difference between M1 samples is found in Fig. 13, suggesting that replenishment ability of M1 grease after 1 000 hours of service is unchanged from new grease.

### 3.3. Contaminated M2 and M3 samples

Two different lubricant behaviors are observed for M2 and M3 greases for increasing amount of revolutions done: samples from outer layer (OUT) and new grease behave in the same way that was described for M1 above (running in is complete before the first 100 revolutions and meniscus with butterfly shape is formed afterwards). On the other hand, inner layer (IN) samples generally do not change the lubricant flow shape seen in Fig. 14 – butterfly meniscus isn't formed. Furthermore, flow of lubricant into the contact does not change between 100 and 1000 revolutions done and total lubricant volume depends only on initial lubricant volume.

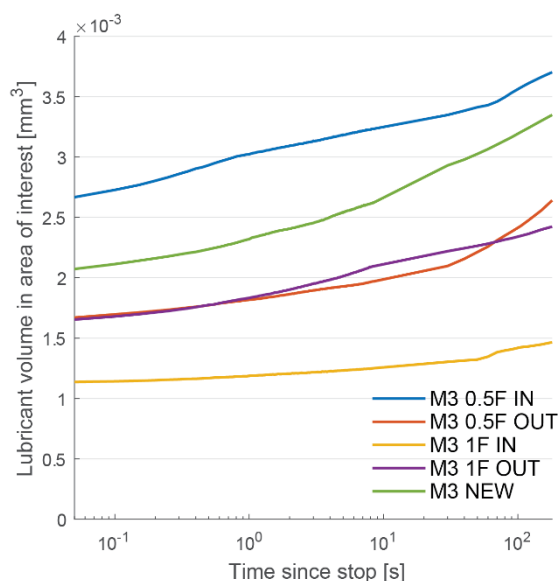


**Fig. 14** M3 0.5F IN 10 rev. (left) and 1000 rev. (right)



**Fig. 15.** Development of lubricant volume for M2 samples at 1000 done revolutions.





**Fig. 16.** Development of lubricant volume for M3 samples at 1000 done revolutions.

Significant deviation in initial and total volumes is found across all M2 and M3 samples in Fig. 15 and Fig. 16. However, no correlation between volume differences and operating load in bearings or sample position has been found.

### 3.4. Contamination analysis

MP contamination of samples is shown in Table 4 and the contamination rates by IO are displayed in Table 5.

**Table 4.** MP contamination of samples.

Grease	Sample	Contamination [% of observed area]
M1	1F IN	0.84
	1F OUT	0.2
	0.5F IN	0.33
	0.5F OUT	0.24
M2	1F IN	13.72
	1F OUT	3.86
	0.5F IN	1.9
	0.5F OUT	1.38
M3	1F IN	39.22
	1F OUT	25.91
	0.5F IN	6.42
	0.5F OUT	16.59

Note that the values are not transferable to contamination % of volume. IO contamination

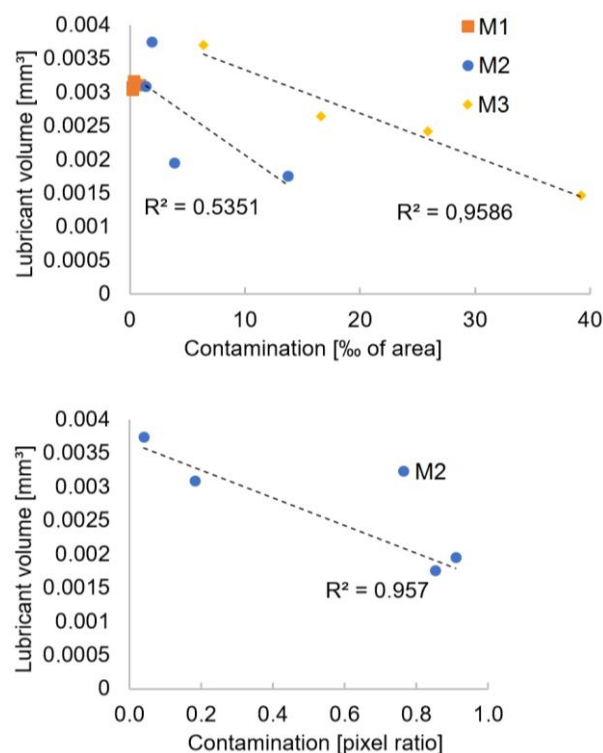
results should be only perceived as auxiliary, because the method used to quantify the contamination is rough in comparison to atomic absorption spectrometry, which would be much more suitable however, was not available.

**Table 5.** IO contamination rates.

Grease	M2			
Sample	1F IN	1F OUT	0.5F IN	0.5F OUT
Contamination ratio [% of observed area]	85	91	4	18

### 3.5. Influence of contamination

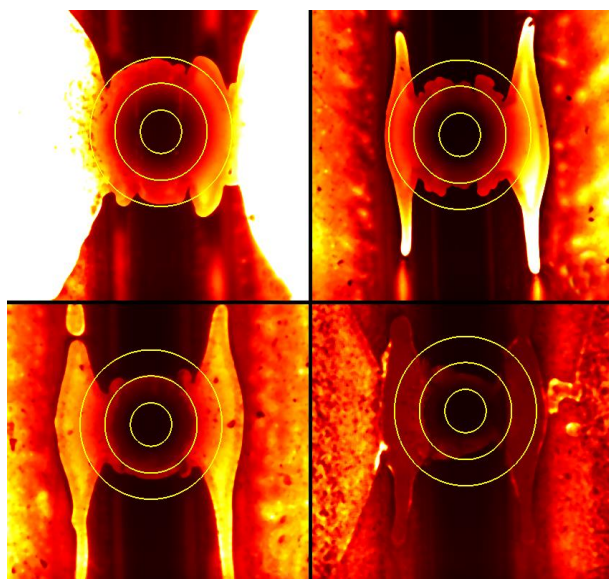
Relationship between observed lubricant volume in area of interest after 180 seconds and contamination value for each sample can be seen in Fig. 17.



**Fig. 17.** Influence of MP contamination (upper), and IO contamination (bottom).

No clear effect is seen for M1 samples, which are contaminated only very lightly. M2 samples show limited correlation with MP contamination ( $R^2=0.54$ ) but correlate closely with IO contamination ( $R^2=0.96$ ). However, coefficient of determination is high partially because M2 samples are divided into two pairs with similar values. Aged M3 samples are heavily contaminated by metal particles and

clear linear dependence ( $R^2=0,96$ ) is observed. This is also visible by cursory examination of M3 shots, one example per each sample is featured in Fig. 18.



**Fig. 18.** M3 samples sorted by increasing contamination at 1000 revs. Done. Up, left - 0.5F IN, up, right - 0.5F OUT, bottom, left - 1F OUT, bottom right - 1F IN.

Contamination rates were identified as closely related to the observed replenishment capabilities of grease. It is not clear whether observed relationship is correlation or causation, however the relationship can be observed while other conditions, such as operating load and position in bearing, differ. Also, sufficient amount of lubricant can be found in distant surroundings of contact with all heavily contaminated samples (M2 1F IN and M3 1F IN (Fig. 18 bottom, right)). This suggests that enough grease is present for sufficient lubrication of contact under usual conditions, but in case of heavily contaminated samples, lubricant is behaving irregularly and will not flow into contact.

### 3.6. Fluorescence limitations

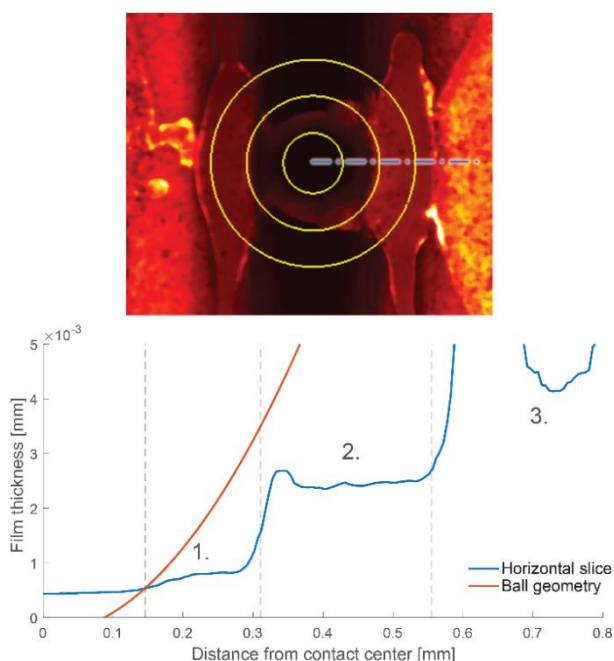
Use of optical fluorescence comes with several inaccuracies. Most of these inaccuracies were corrected but it is not clear how to solve these two: fluorescence quenching induced by contaminants and presence of non-fluorescent thickener in lubricant volume. Both are discussed individually in the two following sections.

### 3.7. Quenching induced by contaminants

First encountered inaccuracy is due to fluorescence quenching, which is decrease of observed intensity values due to presence of certain substances. Chromium is present in 100Cr6 bearing steel and is well documented inhibitor of fluorescence. Its quenching property was utilized for example by Zhang [27] or Rong [28] to measure chromium pollution in water. Iron oxides are fluorescence inhibitors as well, for example Manciulea [29] observed IO interaction with fulvic acid by fluorescence quenching.

Linear dependence of film thickness to intensity values ceases to apply in case of the most heavily contaminated samples (M3 1F IN, M2 1F IN, M2 1F OUT). Lubricant intensity values observed for these samples can be roughly grouped into three groups labeled in Fig. 19:

1. Low intensity: lubricant that was present in the contact at the moment of deceleration (0.15– 0.3 mm from contact center).
2. Medium intensity: lubricant in meniscus that has flown into contact from wider surroundings after stopping (0.35 – 0.55 mm from contact center).
3. High intensity: lubricant present in reservoirs further from contact (can be seen right of meniscus in right picture of Fig. 19).



**Fig. 19.** Intensity/film thickness nonlinearity encountered for heavily contaminated samples.

While butterfly meniscus shape can be observed in Fig. 19, thickness values calculated from intensity do not match expected meniscus geometry (horizontal slice). However, lubricant flows towards the contact after stopping as usual and no irregular behavior is observed. Therefore, presumed film thickness in meniscus is probably present but cannot be observed or evaluated correctly. It is reasonable to assume that the samples were not mechanically worked directly by rolling elements in bearings. Therefore, one possible explanation of described intensity value groups would be that different levels of the quenching effect are observed, depending on how well the chromium has been blended into the sample by repeated mechanical working of the ball during the experiment. However, that would mean that varying lubricant thickness within one group is observed as constant number of intensity values, which is counterintuitive.

Question is that, is the observed effect of contamination on replenishment false, meaning only different levels of quenching were observed? No, because decrease of replenishment can be observed not only by decreasing volume, but also by shrinking meniscus area (as seen in Fig. 18). However, change of meniscus area is much more difficult to quantify. The method used for calibration is unaffected by absolute decrease of observed intensity values. Therefore, there are two conditions for successful calibration of film thickness when quenching is in effect:

1. the linearity between intensity values and film thickness still applies
2. quenching effect is constant throughout the meniscus

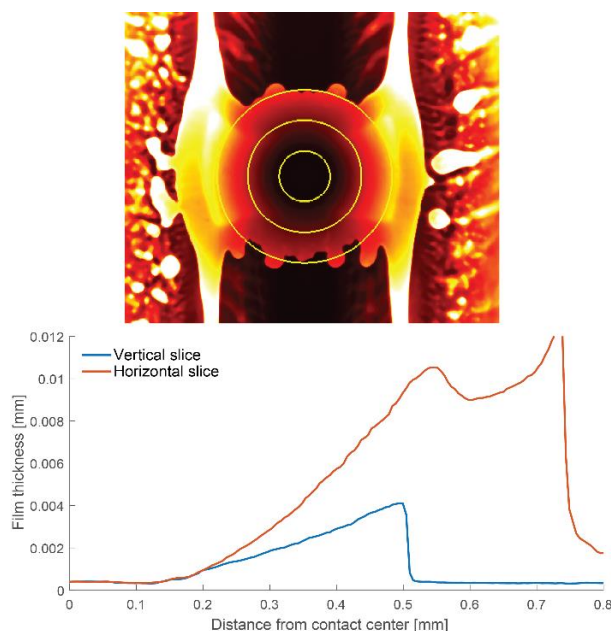
This is the case for all samples except M3 1F IN, M2 1F IN, M2 1F OUT, as mentioned above.

### 3.8. Presence of non-fluorescent thickener

Another observed irregularity that is caused by the nature of fluorescence method can be seen in Fig. 20. Horizontal and vertical slices of M1 0.5F IN with full meniscus are presented. However, film thickness observed in vertical slice is noticeably lower than film thickness in horizontal slice. The most plausible explanation is that the observed lower thickness is caused

by thickener. Thickener is not fluorescent, meaning it essentially acts as an "invisible volume" in meniscus, lowering thickness of the actual bleed oil. No clear answer for removing this effect is apparent.

It can be argued that the "invisible volume" effect is not entirely negative. Bleed oil is the major component of replenishment and lubrication process, so observing flow of only bleed oil volume and not thickener may be beneficial. At the same time, comparability of replenishment across greases with different thickener is limited because of the invisibility. Despite above described obstacles, optical fluorescence is presently irreplaceable tool when investigating wider area around EHL contact.



**Fig. 20.** Meniscus of M1 0.5F IN 100 revs, slices vertical (blue) and horizontal (red).

## 4. CONCLUSION

In-contact replenishment of the grease samples aged for 30 – 50 % of its predicted life in bearings and new grease samples was observed using optical fluorescence. Slight difference within statistical error was found between uncontaminated M1 samples from inner and outer part of bearings. The inner layer could be more degraded from bearing vibrations. However, no significant differences in replenishment or behavior were found between uncontaminated M1 samples. This is in agreement with Lugt [1] who published that

physical properties of grease do not change over long time.

However, the two other greases were contaminated by metal particles (M3) and iron oxides (M2) which suggests lower grease performance. Observed lubricant replenishment is not affected by varying operating loads and points of extraction from bearings. However, strong link between contamination rate and lubricant replenishment was observed for both contaminated greases. Degree of lubricant contamination is suggested as one of possible causes of film collapse in EHL contact and might be also the leading reason for deterioration of the lubricated bearing.

Main findings of this study are:

1. No major change in oil replenishment happens during significant portion of grease life under regular circumstances.
2. Oil replenishment rate significantly decreases with increasing lubricant contamination.

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